Mechanical and Metallurgical Properties of Friction Stir Welded Aluminium Alloy 6061-O

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Abstract. This work reports the effect of process parameters on metallurgical and mechanical properties of friction stir welded aluminium alloy 6061-O. The samples were friction stir welded under tool rotational speed of 1120, 1250 & 1500 rpm and traversing speed of 0.5, 0.6 & 0.8 mm/sec with an axial load of 9000 Kg constant for all the trials. The process parameters were optimized by Taguchi's orthogonal array for better weldment. Microscopic analysis was carried out across various zones of friction stir welded samples (Unaffected Base Metal, Heat Affected Zone, Thermo Mechanically Affected Zone and Nugget Zone). Mechanical tests (microhardness survey & tensile test) were carried out and all the results were correlated with the parent base metal. It is observed from the results that tool rotational speed and traverse speed were a major criterion for welding two alloys in friction stir welding process which decides the weldment quality of the joint produced.

Keywords: Friction Stir Welding (FSW), Metallographic study, Mechanical properties and Taguchi's orthogonal array.

1. Introduction

Aluminium alloys are widely used in various applications around the automotive and aircraft industries because of their light weight properties, better corrosion resistant and high strength to weight ratio. Different welding processes were available for welding light weight alloys among this friction stir welding process is more compatible when compared to other fusion welding processes due to better weld quality [1]. Friction stir welding process is a solid state welding process in which the joint is produced between two alloys both similar and dissimilar [2]. The welding process is carried by means of friction between the parent material and tool, due to a severe stirring process the material gets plasticised and movement takes place from the retreating side to advancing side, the various zones of FSW process can be classified as nugget zone [NZ], heat affected zone [HAZ], thermo mechanically affected zone [TMAZ] and unaffected base metal [UA] on both retreating and advancing sides [3]. Similarly the weldment strength can also varied by the tool pin design such as threaded, square, plain cylindrical, etc., [4].

In the present work two similar aluminium alloys 6061-O were friction stir welded by varying the process parameters such as tool speed, traverse speed and axial load as constant for all the trials. Mechanical and metallurgical properties of above weldments were carried out and the results are discussed.

2. Experimental procedure

2.1 Materials used

The materials used in this work are AA 6061-O (150 x 100 x 6) mm and tool used for stirring process was high carbon steel D3 (hardened to 58-60 HRC), dimensions of the tool are rod diameter 20 mm, shoulder diameter 15 mm, pin probe length 5.7 mm, pin diameter 5.7 mm (pin used is a straight flat cylindrical type). The shoulder of the tool is tilted to 2° for better movement of material from retreating side to the advancing side. The material properties of material and tool were listed in table 1 & 2. The set up was made as per the requirement and the joints were produced by varying the tool speed, traverse speed and axial load of 9000 Kg constant for all the trials.

Table 1. Chemical compositions of AA 6061-O in (Wt %), [5]

Elements	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
Composition	95.8 - 98.6	0.04 - 0.35	0.15 - 0.4	0.7	0.8 - 1.2	0.15	0.4 - 0.8	0.15	0.25

Table 2. Chemical compositions of high carbon steel D3 in (Wt%), [6]

Elements	C	Si	Mn	Cr	V
Composition	2.15	0.40	0.40	12.25	0.25

3. Optimization of process parameter

3.1 Taguchi’s experimental design

Design of experiments (DOE) approach considered to be an important factor in manufacturing to optimize the inputs. Taguchi’s parameter design is an important tool for simple and systematic approach to optimize the design for performance, quality and cost [7]. The experimental design proposed by Taguchi involved orthogonal array which decides the factor which affects the quality with minimum amount of experimentation thus leads in time saving and resources being used in the experiment. Here we followed the process with two process parameters under three levels thus we fall into L9 orthogonal array from Taguchi’s orthogonal array selector [8]. Process parameters used in this experiment were listed in table 3.

Table 3. Process parameter

Experiments (Samples)	Tool Speed (rpm)	Traverse Speed (mm/sec)
1	1120	0.5
2	1120	0.6
3	1120	0.8
4	1250	0.5
5	1250	0.6
6	1250	0.8
7	1500	0.5
8	1500	0.6
9	1500	0.8

3.2 Grey relational analysis (GRA)

Grey relational analysis is the tool which leads to optimize a multi response parameter to a single response in order to achieve the optimal process parameter, from the grey relational grade values the ranks were allotted for each parameter used. It has both larger the better and smaller the better expressions, we had utilized larger the better expression values because higher the hardness value gives better weld strength [3]. From the calculated values, the table 4 shows that sample (6) seem to be an optimal process parameter from the chosen set of parameters. Larger the better can be expressed as below.

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (1)$$

Where,

$x_i(k)$ - Value after the Grey relational generation.
$\min y_i(k)$ - The smallest value of $y_i(k)$ for the kth response.
$\max y_i(k)$ - The largest value of $y_i(k)$ for the kth response.

Grey Relational Coefficient can be expressed as follows

$$\P_i(k) = \frac{\Delta_{\min} - \cdot \Delta_{\max}}{\Delta_{0i}(k) + \cdot \Delta_{\max}} \quad (2)$$

Where,

Δ_{oi} = $\left|x_0(k) - x_i(k)\right|$

Ψ = 0.5

$\Delta_{\min}$ = $\left|x_0(k) - x_j(k)\right|$

Δ_{max} $= \left| x_0(k) - x_j(k) \right|$

Grey Relational Grade

$$¥_i = \frac{1}{n}\sum_{k=1}^{n} ¶_i(k) \tag{3}$$

Where,

y_i - Grey relational grade.

n - Number of process responses.

Table 4. Larger the better values of friction stir welded samples AA 6061-O

Experiments (Samples)	Tool speed (rpm)	Traverse speed (mm/sec)	Micro hardness value (µ HV)	Normalized value	Grey relational coefficient	Grey relational grade	Rank
1	1120	0.5	49.48	0	0.3333	0.03703	9
2	1120	0.6	53.76	0.4687	0.4848	0.05386	4
3	1120	0.8	50.38	0.0985	0.3567	0.03963	8
4	1250	0.5	52.3	0.3088	0.4197	0.04663	6
5	1250	0.6	55.19	0.6254	0.5716	0.06351	3
6	1250	0.8	58.61	1	1	0.11111	1
7	1500	0.5	52.62	0.3439	0.4324	0.04804	5
8	1500	0.6	51.71	0.2442	0.3981	0.04423	7
9	1500	0.8	56.38	0.7557	0.6717	0.07463	2

4. Results and Discussions

4.1 Metallographic analysis

All the samples were friction stir welded under different tool and traverse speed. Samples were polished and etched using Keller’s reagent which is most suitable for all the aluminium alloys. Optical microstructures were observed for sample number 6 across various zones (Unaffected base metal, heat affected zone, thermo mechanically affected zone and nugget zone) both retreating and advancing sides based on the optimization results obtained by (GRA) are shown in Fig. 1 (a-h). Fig. 1(a) shows base metal microstructure with equiaxed grains, with relatively uniform grain structures [9, 10]. It is also inferred from the NZ Fig. 1 (d) refined formation of grains due to stirring process across the weld bond, considerably correlating the TMAZ zone on both sides Fig. 1 (e & f) that there is an increase in grain structure which leads to deterioration of tensile properties [11]. From Fig. 1(g & h) the HAZ grains were less recrystallized to that of TMAZ zone, similarly material flow from the advancing side to retreating side can be seen from Fig. 1(e). Compared to the base metal the unaffected base metal of welded sample showed less equiaxed grains due to heat generation during the process Fig. 1(b & c). Correlating the metallurgical properties of weldments (various zones) with base metal it resulted in better refined grain structures due to material transfer from retreating to advancing side.

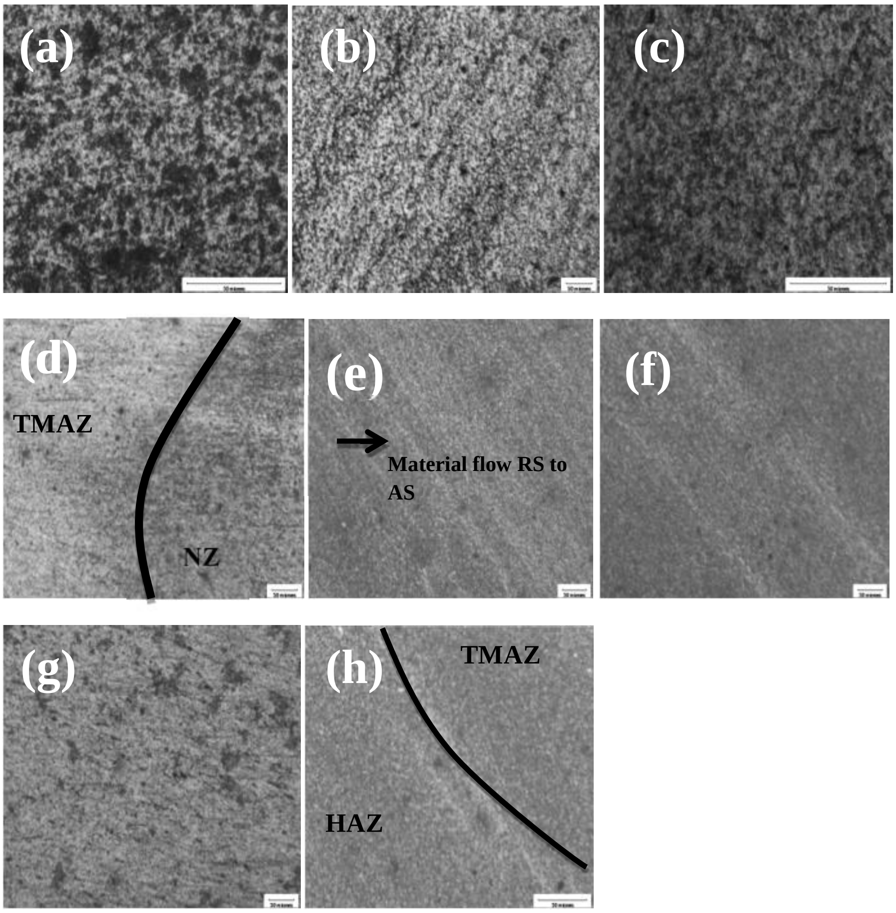

Fig. 1: Optical microstructures of sample number 6 weldment - (a) Base metal, (b) UA base metal – AS, (c) UA base metal – RS, (d) NZ, (e) TMAZ – AS, (f) TMAZ – RS, (g) HAZ – AS, (h) HAZ - RS

4.2 Tensile properties

The ultimate tensile strength (UTS) for the weldments was evaluated using a tensile testing machine Fig. 2 shows the tensile properties profile of weldments all the samples were prepared as per (ASTM E08) standard for testing Fig. 3. Compared to the base metal, friction stir welded samples showed better tensile properties due to the stirring process and plasticization of material. The UTS value is increased with the increase in traverse speed which results in defect free joint and better UTS value to that of base metal, further increase in traverse speed resulted in decreased UTS value [12]. UTS values were listed in table 5.

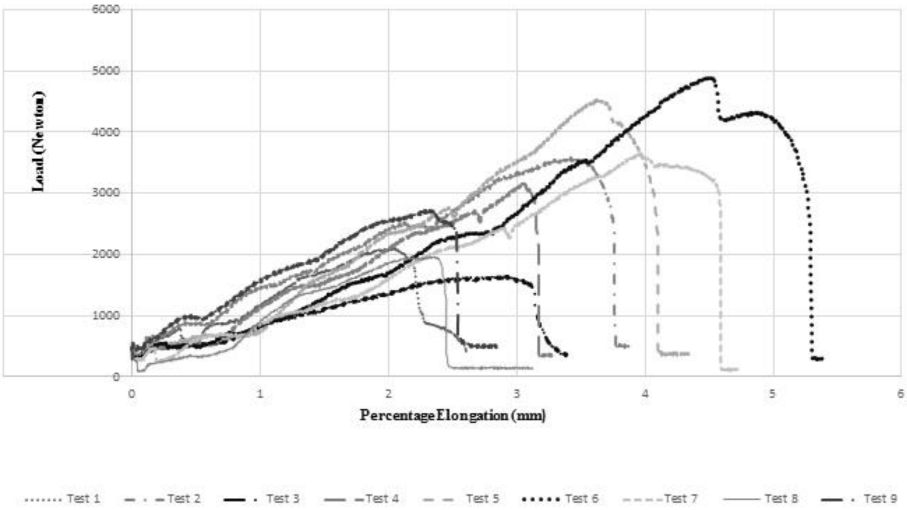

Fig. 2 Tensile properties of welded samples

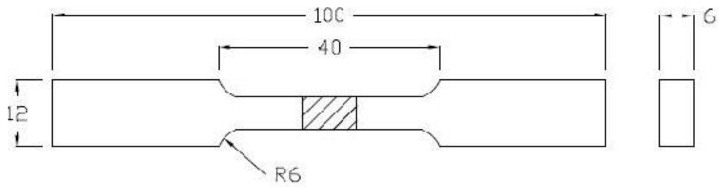

Fig. 3 Dimensions of tensile specimen (ASTM E08) (Units in mm)

Table 5. Tensile properties of friction stir welded AA 6061-O

Experiments (Samples)	Experimental UTS (Newton)	Percentage Elongation (mm)
1	2112	2.02 ± 0.2
2	3562.5	3.42 ± 0.2
3	1637.5	2.95 ± 0.2
4	3162.5	3.05 ± 0.2
5	4512	3.66 ± 0.2
6	4887	4.51 ± 0.2
7	3637.5	3.97 ± 0.2
8	1962.5	2.36 ± 0.2
9	2725	2.25 ± 0.2

4. 3 Microhardness test

Fig (4) shows the microhardness profile for the welded samples. Base metal has a 40 µ HV microhardness value [13]; compared to the base metal the welded samples resulted in better hardness property due to material movement. In the present experiment the failure occurred in TMAZ zone which is very adjacent to weld nugget which resulted in higher hardness value in the nugget zone [14]. Also from graph it is inferred that hardness values were similar in the TMAZ and HAZ zone both retreating as well advancing side due to plasticization of material. The UA base metal showed some deviations in the hardness value when compared to the base metal due heat transfer from the adjacent zones of the weldments.

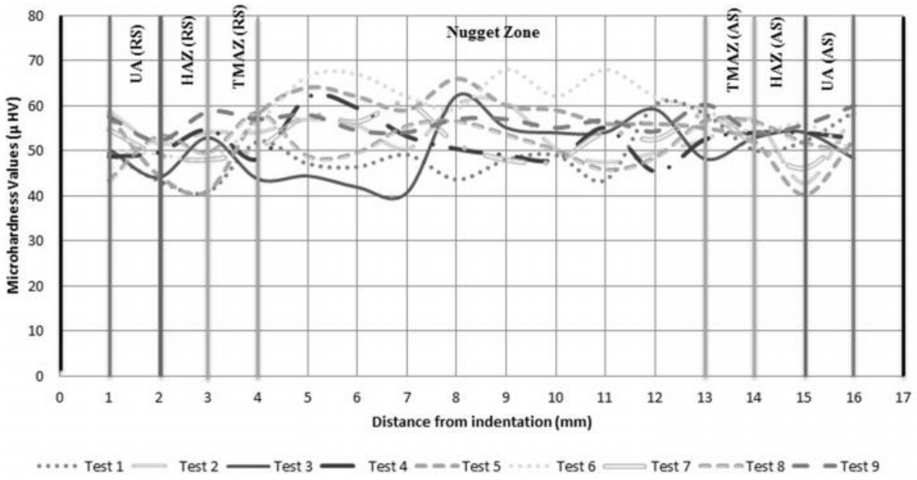

Fig. 4 Microhardness values of welded samples

5. Conclusion:

In the present work mechanical and metallurgical properties of friction stir welded similar aluminium alloy joints was investigated. The following conclusions are made

(1) Successful joints were made on similar aluminium alloy 6061-O by friction stir welding process.
(2) Process parameters are optimized using Taguchi's orthogonal array.
(3) Metallurgical survey were carried on parent base metal and across the various zones of weldments (UA base metal, TMAZ, HAZ, NZ) on both retreating & advancing sides.
(4) Tensile strength of the weldments showed a better result to that of base metal.
(5) Microhardness values showed better enhancement when correlated with base metal due to the movement of material and severe stirring process.
(6) Comparing with the mechanical, metallurgical properties and optimized process parameter it is revealed that tool speed of 1250 rpm, traverse speed of 0.8 mm/sec and axial load of 9000 Kg resulted in a defect free joint among all other parameters used in this work.

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